
On The Anomalies In Single-Jet Hover Suckdown Data

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SYMBOLS

A_j	jet exit area, ft ²
A	plate area (used in fig. 13), ft ²
AR	planform aspect ratio
d	jet exit diameter, ft
$d\phi$	angular increment, rad.
D	plate diameter, ft (jet dia. in fig. 13)
\bar{D}	angular mean diameter of planform, ft (as defined in ref. 2), $\bar{D} = \frac{1}{\pi} \int_0^{2\pi} r d\phi$
h, H	height above ground, ft
ΔL	jet-induced lift, lb
ΔL_∞	jet-induced lift out of ground effect, lb
NPR	nozzle pressure ratio
p	pressure, lb/ft ²
p_a	atmospheric pressure, lb/ft ²
p_n	jet total pressure, lb/ft ²
q_j	jet dynamic pressure at exit, lb/ft ²
q_x	dynamic pressure at distance x from exit, lb/ft ²
r	radial station, ft
R	radius of nozzle, ft
S	planform area, ft ²
T	jet thrust, lb
x	distance downstream from jet exit, ft

ON THE ANOMALIES IN SINGLE-JET SUCKDOWN DATA

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SUMMARY

The data from nine different investigations of the suckdown induced in ground effect by a single jet issuing from plates of various sizes and shapes have been examined and compared. The results show that the generally accepted method for estimating suckdown significantly underestimated the suckdown for most of the configurations.

The study identified several factors that could contribute to the differences. These include ground board size, plate edge effects, jet flow quality, jet impingement angle, the size of the chamber in which the tests were run, and obstructions in the region above the model. Most of these factors have not been investigated and in many cases items such as the size of the test chamber, jet flow quality, ground board size, etc., have not even been shown in the documents reporting the investigation. A program to investigate the effects of these factors is recommended.

INTRODUCTION

The induced effects experienced by jet V/STOL aircraft hovering in close proximity to the ground have been the subject of many investigations over the past 30 years. In general, the flow phenomena involved are well known, but our ability to predict the forces and moments that will be encountered is poor, particularly for multiple jet configurations. Even for the simple case of the ground effects on a single jet issuing from the center of a flat plate, there are anomalies in the data base that have not been explained. This paper will examine these anomalies and attempt to explain them and/or outline investigations that should be undertaken to investigate the reasons for the differences.

This review was precipitated by the recent results from an investigation initiated by the NASA Ames Research Center to study the hot gas ingestion and suckdown characteristics of jet STOVL fighter type configurations. Reference 1 is a data report on the first of this series of tests. In order to evaluate the adequacy of the test setup in which the investigation was to be conducted the suckdown induced by a single jet on a circular plate was measured in the test cell and in a much larger chamber (the high bay area of the 40- by 80-Foot Wind Tunnel at Ames). The results showed only a small effect of the size of the test cell, but both sets of results indicated much more suckdown than predictions by the method of reference 2, which has been the generally accepted standard.

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Similar anomalies in single-jet suckdown data have been noted before in reference 3. The present paper reviews all the single-jet suckdown data available to the authors, attempts to identify the reasons for the differences in the results, and defines the correct data base and method for estimating single-jet suckdown.

RESULTS OF CURRENT TESTS

Models and Test Setup

The NASA Ames Research Center has initiated a program to study, on the same model and test setup, both the suckdown and hot-gas ingestion experienced by jet STOVL fighter configurations in ground effect. The bulk of the testing was to be done in the test cell shown in figure 1 because of the availability of heated high-pressure air for the hot-gas ingestion part of the program. However, there was some concern that the test cell may be too small and that flow recirculation within the test cell may produce results that are not representative of true hovering.

As one step in evaluating the adequacy of the test setup and of the size of the test cell, the suckdown induced by a single jet on a circular plate was measured for comparison with the levels predicted by the method of reference 2, which has been the generally accepted standard. In addition, tests of the same plate with the same nozzle were repeated in a much larger test area, the high bay area of the 40- by 80-Foot Wind Tunnel at Ames. This high bay area is 124 by 180 by 116 feet high and should be free of any recirculation effects.

The test setup used is shown installed in the test cell in figure 2. The model is supported on a strain-gauge balance from an overhead beam, which is in turn supported by two "A" frames. For tests of multiple jet configurations the nozzles are installed on plenum chambers, which are also supported from the overhead beam. For the circular plate test the single jet was installed on the rear plenum, as shown in figure 2.

Because the plate was mounted on the balance so that only the induced loads are measured, a gap of about 0.05 inches is maintained around the nozzle, as shown in figure 3. Pressure distributions measured on the plate with this gap open and with it sealed indicated that the effect of the gap was to reduce the suckdown measured on the plate by less than 1 percent of the measured suckdown. An ASME long-radius flow nozzle, as defined in reference 4, was used to produce the jet. The jet thrust was calculated from the total pressure measured by a Kiel probe installed upstream of the ASME nozzle, as shown in figure 3.

An 8-ft by 8-ft steel-and-aluminum groundboard, installed below the model, was raised and lowered by a hydraulic lift below the groundboard to change the height above the ground. For the "out-of-ground-effect" end point the ground board and hydraulic lift mechanism were removed and the plate was 8 ft above the floor of the test cell.

The same plate, balance, nozzle, Kiel probe, and plenum chamber were used in the tests in the 40 by 80 high bay area; however, the setup was inverted so that the nozzle exhausted upward. An

8-ft by 8-ft plywood groundboard was used for these tests, and it was raised and lowered by a mechanism off to one side of the groundboard. This groundboard was removed for the out-of-ground-effect end points, leaving about 108 ft clearance between the plate and the ceiling of the high bay area. The suckdown on a 10 in. diameter plate was also measured in the tests in the high bay area. Except for its diameter this plate and its mounting were identical to the 20 in. plate.

Results

The increment of lift loss induced on the plates by ground proximity, as measured in the test cell and in the high bay area, are compared in figure 4. In this presentation the lift loss measured out of ground effect (fig. 5) has been subtracted from the data measured in ground effect and plotted against the height parameter developed by Wyatt in reference 2. There appears to be a large amount of scatter at the greater heights, but this is largely due to the fact that this is a log plot. The deviation from the faired line is less than 1 percent of the thrust and usually less than about 1/2 percent of the thrust. The data show that at the higher nozzle pressure ratios (above about 3.5) the jet-induced lift loss at the lower heights is reduced and the reduction is the same in the test cell as in the high bay area.

Comparison of the data shows that the ground-induced lift loss measured in the test cell is greater than in the high bay area (which is assumed to be interference-free). However, the difference is small: only about 1/2 of one percent of the thrust and, except for some data from the 10 in. diameter plate taken in the high bay area, the differences appear to be independent of nozzle pressure ratio. The reasons for the deviations in the 10 in. diameter disk data are unknown and will be the subject of further investigation.

The "out-of-ground-effect" data (fig. 5) also show more (but less than 1/2 percent of the thrust) jet-induced lift loss in the test cell (door open) than in the high bay area. This lift loss is in addition to that induced by the ground; however, the total induced lift loss measured in the test cell is still less than 1 percent of the thrust greater than what would be experienced in free air.

The "out-of-ground-effect" data taken in the test cell (fig. 5) show that closing the door at the end of the test cell increased the induced lift loss. Apparently, opening the door reduced the recirculation within the test cell. All the data taken in ground effect were taken with the door open.

COMPARISONS WITH PREVIOUS RESULTS

The results from both the test cell and the high bay area (fig. 4) indicate much higher ground-induced suckdown than predicted by the method of reference 2. (The comparison is only shown at a pressure ratio of 1.5 because the reference-2 data were taken at pressure ratios of 1.5 and lower.) It is this major difference in the results that has prompted the present review. As will be discussed in later sections (and as also discussed in reference 3), some other investigations also show more suckdown than predicted by reference 2. Apparently there are differences in the test conditions, jet characteristics, or other factors that are causing these discrepancies.

Close to the ground, it is primarily the entrainment action of the wall jet flowing outward from the jet impingement point that induces the lower pressures and the suckdown. In searching for the causes of the anomalies, the factors that could change the entrainment action of the wall jet must be considered. It has been shown in reference 5 that, out of ground effect, the suckdown is proportional to the decay rate of the jet stream. That is, an increase in entrainment rate increases the inflow across the planform with a proportionate lowering of the surface pressures and this increase in entrainment rate also increases the mixing rate and decay rate of the jet. Anything that could change the entrainment rate of the wall jet or its decay rate could also change the suckdown. Factors that could be considered include the jet characteristics (turbulence, temperature, exit profile, decay rate in free air), ground surface texture, and perhaps the size of the ground board. (Does the mixing on both sides of the wall jet when it flows off the edge of the ground board influence the flow in the wall jet on the board, and how close to the edge of the planform is this felt?)

The shape of the edge of the planform may also have an effect. With a sharp edge the induced flow will separate; with a rounded edge the separation will be reduced and the suction pressures at the edge and the associated lift loss will also be reduced. There are no data available to evaluate these effects. How sensitive is the pressure distribution and suckdown to the edge shape?

If the chamber in which the tests are made is too small, the flow in the wall jet would not have sufficient distance to fully dissipate, and unsteady recirculation flows would be set up in the chamber. The resulting gusts experienced by the model would produce an additional suckdown. The data of figure 4 suggest that this effect is small for the test cell used in the present investigation. It also suggests that the difference between the present results and those of reference 2 could not be due to room size. If room size were the only factor and the tests of reference 2 had been done in a very small room, the suckdown would be larger, rather than smaller, than the present results.

There have been few systematic investigations of any of the above factors that could affect the suckdown, and the reports on past investigations seldom report such items as details of the jet characteristics, ground board size, room size, or model edge shape. The following sections will make comparisons with earlier results, review what is known about their test conditions, speculate on what may be causing the differences noted, and make suggestions for future studies required to clarify the situation.

Comparison with Wyatt—The British began studies of jet VTOL aircraft in the late fifties and initial ground effect tests were published by Wyatt in reference 6 (initially published as A.R.C. 20369). This work was followed by a systematic investigation of the effects of planform size and shape, and the development of an empirical expression for estimating suckdown reported in reference 2. Shortly after Wyatt's work, Hall (ref. 7), using a J-85 engine as the jet source in a full scale study, obtained results in good agreement with Wyatt's. These results seemed to indicate that any scale effects or real jet effects on suckdown were negligible and Wyatt's method for estimating suckdown became accepted as the standard.

The experimental setup used in the investigation of references 2 and 6 is shown in figures 6, 7, and 8 (reproduced from ref. 6). The room size is not indicated; however, room size is probably not a factor in the comparison between the present results and those of reference 2. As indicated above, if

the data of reference 2 were taken in too small a chamber, and room size were the only difference, the suckdown presented in reference 2 would be larger, rather than smaller, than the present results.

In both the present study and the investigation of reference 2, the plates on which the suckdown was measured were mounted independent of the nozzles. The nozzle of the present investigation had a relatively sharp edge (fig. 3), whereas the nozzle used in the reference 2 study had an appreciable wall thickness (fig. 8). Wyatt recognized that suckdown measured on his setup would be reduced by this thick wall and the gap needed between the nozzle and the plate. He estimated the effect to be about 3 to 6 percent of the suckdown and adjusted the constant in his expression for estimating the suckdown to account for this difference.

In the present investigation, the edge of the plate was beveled as shown in figure 3. The models used in reference 2 had square edges as shown in figure 7. The effects of edge shape on the suckdown have not been investigated. A rounded edge may reduce the suction pressures near the edge, but it is hard to believe that the difference between the beveled edge of the present investigation and the square edge of the investigation of reference 2 could account for the differences shown in figure 4. Nevertheless, future investigations should include studies of the effects of thickness and edge treatment (sharp, square, and rounded with various radii).

Reference 6 indicates that the jet used in the investigation of reference 2 had a uniform velocity distribution (fig. 8). Unfortunately, the velocity profiles at some distance from the exit (to determine the decay rate of the jet) are not presented. However, the out-of-ground-effect suckdown is high. Reference 5 showed that the suckdown induced out of ground effect is proportional to the decay rate of the jet. The suckdown measured out of ground effect in reference 2 is compared with that presented in reference 5 for several jet/plenum-chamber combinations at the top of figure 9. The round plenum chamber of reference 5 was well formed and produced a jet with the decay curve (bottom of fig. 9) starting at about 5 diameters (a potential core about 5 diameters long) indicating a good, clean, well-formed jet. This produced the smallest suckdown out of ground effect. Introducing an obstruction in the nozzle increased the mixing rate, the jet decay rate, and the suckdown.

On the other hand, the rectangular plenum (which was intended to fit inside a model fuselage), even with modifications to improve the internal flow in the plenum, produced a more rapid decay rate and greater suckdown than either circular jet/plenum configuration. The data from reference 2 show even more suckdown than this "improved plenum" configuration, suggesting that the quality of the flow in the jet may have been poor. Figure 6 (from ref. 6) indicates that the air line feeding the air to the nozzle included a 90° bend immediately upstream of the nozzle. This could have induced swirl and angularity into the flow which were not measured.

The suckdown (out of ground effect) measured in the present tests is compared with the data from references 2 and 5 in figure 10. In this figure the suckdown parameter is divided by the square root of the planform-to-jet area ratio, so that data from different jet/planform size combinations can be compared. The reference 5 data from the "clean/circular" jet/plenum configuration is in good agreement with the present data from the test cell with the door closed. The size of the room in which the tests reported in reference 5 were run is not reported, but the senior author remembers it as having about the same ceiling height as the test cell of the the present investigation (fig. 1) with the length and width about 50 percent greater. The jet diameter was about twice that of the present tests,

so that the size of the room relative to the jet was slightly smaller than the configuration of the present tests. The presentation of figure 10 suggests that the out-of-ground-effect data of reference 5 may not represent true "free air" conditions and may be high by a factor of about 2. Figure 10 also suggests that the data of reference 2 may have been taken in a very small room or that the jet was of poor quality, as discussed above.

The exit profile and decay curve for the jet used in the present tests are presented in figure 11. The decay curve is almost as good as the clean/circular jet/plenum combination of reference 5, but the exit profile taken only 0.1 diameter downstream of the exit shows an unexpected falloff in total pressure toward the edges. (These data are for a nozzle pressure ratio of 1.5.) These data are inconsistent with the discharge coefficient calculated by the method of reference 4 and used in the calculation of the thrust to nondimensionalize the data. The actual thrust may be 3 to 5 percent lower than calculated. However, since the suckdown was measured directly and the thrust occurs in the denominator, this error in the thrust would have less than 1/2 percent effect on the lift/thrust ratios from the present tests. It cannot explain the larger differences between the present results and reference 2.

The presence of the 90° bend in the feed line immediately upstream of the nozzle used in the reference 2 investigation suggests that the flow may not have exited the nozzle parallel to the center line. Flow angles of a few degrees may not have shown up on the exit-velocity profile but would be expected to produce an asymmetrical velocity distribution in the radial wall jet on the ground. The data of reference 12 (to be discussed later) indicates that the suckdown is proportional to the square of the sine of the angle at which the jet impinges on the ground. This would indicate that, to produce the differences shown, the jet would have to be deflected more than 30° from the center line, which is hardly likely. However, jet deflection may be a contributing factor and should be investigated.

Recent unpublished results indicate that obstructions near (but not attached to) the "top" side (side from which the downflow induced by the wall jet is approaching) of the model can reduce the suckdown measured on the model. The mechanism involved is not fully understood, but apparently blockage to the downflow induced by the wall jet on the ground in some manner "shields" the model from the downflow and reduces the suckdown. In the investigations of references 2 and 6 the jet was supported from the floor and, although the sketch of the rig is indicated as not being drawn to scale, the model and the ground board appear to be relatively close to the floor of the test cell. The presence of the test cell floor may be inhibiting the wall jet induced inflow and thereby reducing the suckdown. Unfortunately, there are no data available that could be used to estimate these effects. An investigation of the effects of blocking surfaces on the "top" side of the model is needed.

This comparison of the rigs and data of the present and reference 2 investigations has not revealed any clear cut reasons for the differences in the results obtained. However, the effects of several variable should be investigated. These include the effects of (1) blocking surfaces on the down flow side of the model, (2) jet angularity, (3) planform edge shape, (4) ground board size, (5) nozzle edge and gap effects, (6) jet characteristics (turbulence, jet decay, etc.) and (7) wall jet characteristics (was roughness, wall jet decay, etc.).

Comparison with Hall—As indicated above, shortly after Wyatt's work (ref. 2), Hall conducted a full scale investigation using a J-85 engine as the jet source (ref. 7) and obtained results that were in good agreement with Wyatt's data (fig. 12). These results seemed to indicate that any scale effects or

real jet effects on suckdown in ground effect were negligible and Wyatt's method for estimating single-jet suckdown was accepted as adequate. A more recent full scale experiment using a J-97 engine (ref. 13, to be discussed later) however shows much higher suckdown close to the ground.

Reference 7 is an Engineering Note in the AIAA Journal of Aircraft and is therefore brief. Little is mentioned about the experimental setup. Because an actual engine was used it is assumed that the tests were run outside. Was the real ground used (this would have required modifying the engine lubrication system for the engine to run "on end") or was the engine horizontal? How big was the groundboard and how far from the real ground? How was the planform constructed and what was the edge condition? Were there obstructions on the "down flow" side of the planform?

The suckdown data presented by Hall (ref. 7) were obtained on a square plate with the same ratio of planform area to jet area as the largest model of reference 8; $S/A = 142$. However, the reference 8 results (fig. 12) show about 50 percent more suckdown than either Hall's data (ref. 7) or Wyatt's prediction (ref. 2). This discrepancy between the reference 8 data and Wyatt's was pointed out by Wyatt in reference 2 and has not been resolved.

Hall's suckdown data were obtained by integrating the pressures induced on the plate however the only pressures data presented are those shown in figure 13. These data do not show a 50 percent difference between the reference 7 and 8 results. More details of the pressure distributions, the number and locations of orifices and the symmetry or asymmetry of the distributions are needed to understand the results.

Comparison with Spreemann and Sherman—Prior to Hall's work Spreemann and Sherman investigated the ground effects on plates of various sizes and shapes. As indicated above they showed suckdown about 50 percent greater than Hall's or Wyatt's work. Their results show good agreement with the present study close to the ground (fig. 14) but show more suckdown at the higher heights (although the differences are only about 1 to 2 percent of the thrust). Part of the difference at the higher heights, and the scatter, may be due to the difficulty of picking up the data from their figures.

Part of the problem with the data of reference 8 is due to the fact that the planform was not supported on its own balance for direct measurement of the suckdown. The increments due to ground proximity had to be obtained by subtracting the jet thrust measured with the planform removed from the net force in ground effect—the typical small difference of large numbers problem. Also there may have been interference between the structure that supported the plenum-chamber/jet/planform assembly.

The jet was produced from a plenum with a large contraction ratio but used a straight pipe of about 6 diameters in length without a contraction at the nozzle. The plenum/nozzle assembly was used later in reference 9 and was found to have a very rapid decay rate, probably because of the manner in which the air was introduced into the plenum and because no damping screens were used. The out-of-ground-effect lift losses were not measured but were probably high.

The tests of reference 8 were taken with a 1 in. diameter jet in a room that was 18.5 ft wide by 42.5 ft long with a 10 ft ceiling height. Thus the room was about the same size relative to the jet as

the test cell of the present tests (fig. 1) and the room size effects should have been about the same as experienced in the present investigation.

Because of the various potential problems with the data of reference 8 it was not taken seriously by the technical community after Wyatt's method for estimating suckdown became available. However the present review indicates that the reference 8 data is in close agreement with a large body of the available data.

The data of reference 8 are also presented in figure 15 which is taken from reference 10. In this figure and in reference 10 the data from reference 8 are in error. The values of \bar{D} for the reference 8 data were calculated using an incorrect planform area. Figure 14 presents the correct comparison of the reference 8 data with Wyatt's (ref. 2) data.

Comparison with Gentry and Margason—The effects of various nozzle/plenum/planform combinations on the out of ground effect lift loss was investigated in reference 5. In addition the ground effects produced by three plenum/nozzle/ planform configurations were determined. In developing the method presented in reference 10 Kuhn found the ground effects on the wing/body configuration to be in good agreement with Wyatt's data and two other references (fig. 15). The height parameter for the data from reference 5 and 11 was nondimensionalized using the \bar{D} based on the total wing/body planform. (As noted above, the data of reference 8 presented in figure 15 are based on an incorrect \bar{D}).

Only the wing/body single-jet data of reference 5 was used in reference 10 because the objective of reference 10 was to investigate methods for predicting multiple jet ground effects and the multiple jet data of reference 5 was obtained with the wing/body configuration.

Two other sets of single-jet data are available in reference 5. Both using a circular planform, one on the circular plenum and the other of the "improved" rectangular plenum. These data are compared with the present results and Wyatt's data in figure 16(a). For unknown reasons the circular plate on the circular plenum was not carried to low heights and there is considerable scatter in the data but both these data and the data for the circular plate on the rectangular plenum are closer to the present results than to Wyatt's. The deviation at the higher heights is only about 1 percent of the thrust or less.

Figure 16(b) presents another look at the wing/body data. In this figure the \bar{D} on which the height parameter is based is calculated from the wing area alone rather than from the total wing/body planform area. Again, at low heights, the results are closer to the present results than to Wyatt's data. The deviation at the higher heights is about 1 to 2 percent of the thrust. These results call into question the method of defining \bar{D} as used in reference 10. The body, particularly ahead of the wing, is round and the "planform width" of the body occurs above the plane of the wing (only low wing data were used in these comparisons). Figure 16(b) suggests that the body extending forward and aft of the wing planform may not contribute significantly to the suckdown at low heights but may be a factor at the higher heights. Investigations using special flat plate, square and round bodies fore and aft of a wing should be undertaken to clarify this point.

Comparison with Vogler—Wing body hover suckdown data was also obtained as “end points” of the investigation presented in reference 11. There is considerable scatter in these data, but as shown in figure 17(a) they are in general agreement with Wyatt’s data when the \bar{D} based on the total wing/body planform area is used. However, when the \bar{D} based on only the wing area is used the agreement is better with the present results (fig. 17(a)).

Some body alone data is also available in reference 11 and these data are compared with Wyatt’s data and the present results in figure 17(b). The height parameter used in plotting these data is based on the projected planform area of the body. The body had a flat “square corner” center section but a rounded forebody and “squarish” afterbody with round corners. This comparison indicates, as was suggested above, that the \bar{D} should not be based on the projected planform and that an investigation of the effects of body shaping on the definition of \bar{D} is needed.

Comparison with Stewart and Kuhn—Reference 12 was an investigation of the ground effects on jet V/STOL configurations in the transition speed range, however some zero speed “hover” end points were taken. These data were taken in the wind tunnel test section in which the rest of the program was run and significant recirculation of the flow was observed during the tests. The suckdown measured on two of the flat plates used in the study were presented in reference 12 and compared with estimates made by a modification of Wyatt’s method. The experimental data showed much higher suckdown than predicted and the difference was attributed to the flow recirculation within the test section.

The data are compared with the results of the present study and with Wyatt’s data in figure 18 and show good agreement with the present results. Since, as shown above, recirculation was not a significant factor in the present results, it can now be concluded that the recirculation observed in reference 12 did not materially affect the suckdown.

Comparison with Christiansen—Christiansen (ref. 13) conducted another large scale investigation using a J-97 engine. His results (fig. 19) show considerably more suckdown at low heights than predicted by Wyatt but are in good agreement with the present results. At the higher heights they are closer to Wyatt but are within about 1 percent or less of the present results. Also his results show no effect of nozzle pressure ratio in the NPR range he could cover (fig. 20). This result is also in agreement with the results of the present study.

Comparison with Benepe—In an effort to find the reason for the difference in results between Christiansen’s results and the suckdown predicted by Wyatt’s method NASA Ames contracted with General Dynamics for a very carefully conducted scale effect study using a 1/10 scale model of Christiansen’s setup (Benepe, D. B. Sr.: Effect of Scale on V/STOL Operation in Ground Proximity for a Turbojet Engine. Unpublished contractor report.). The results of the first tests with the 1/10 scale model were in general agreement with predictions based on Wyatt’s method and therefore much lower than Christiansen’s large scale data, indicating a large scale effect. The investigation then concentrated on determining the reasons for the scale effect. In the first part of the study primary emphasis was placed on duplicating or trying to determine the effects of the jet characteristics—exit profile, temperature, NPR and turbulence. Typical results at NPR = 1.4 (for comparison with Wyatt’s data) are presented in figure 21.

The effect of variations in the jet characteristics on the suckdown induced out of ground effect was not investigated but one figure (fig. 22 in the Benepe report) showed a lift loss of 2 percent for the 1/10 scale model and 2.5 percent for the full-scale model at height of infinity. These are very high values. The data of reference 5 and figure 10 suggest that for the planform to jet area ratio of this configuration the lift loss should be only about 0.3 percent. The level shown suggests that the large-scale model was subject to interference of unknown origin. (Perhaps the fact that the engine was set up horizontally, so that the actual ground interfered with the inflow induced by the jet entrainment, contributed to higher than expected lift loss?)

The higher than expected lift loss out of ground effect for the 1/10 scale model could be due to test cell size, interference in the test cell, or to jet decay characteristics. A full jet decay curve was not presented but surveys of the jet at 5.6 diameters from the exit show only a small drop in dynamic pressure, thus suggesting that abnormal jet characteristics cannot be blamed for the high suckdown out of ground effect.

The sensitivity of the ground induced lift loss to the out-of-ground-effect increment which was subtracted from the data is shown in figure 21(a). For the remainder of this review of the Benepe report, the estimated lift loss of 0.3 percent on the thrust was subtracted from the data to account for the out-of-ground-effect increment.

In the first part of the study the jet temperature, pressure ratio, and exit flow distribution of the full-scale jet were matched. Provision was also made to introduce turbulence generating screens in the flow to the nozzle. The results are summarized in figure 21(b). The small-scale data are generally close to the estimate based on Wyatt's data and show levels of suckdown due to the ground of about 2/3 of the full-scale results indicating a significant scale effect. Changes in jet temperature and turbulence did not explain these scale effects.

It was suggested in Benepe's initial report that the parameter that needed to be matched was the turbulence level in the jet shear layer. Therefore a second phase was instituted to attempt to evaluate this effect. For this phase a new nozzle assembly was constructed that could also be used later to study the scale effects of a turbofan configuration. This nozzle assembly included provision for the installation of shear layer "trips" in the flow passage just upstream of the nozzle so that the effects of different levels of turbulence in the shear layer could be evaluated. The results shown in figure 21(c) indicate that these shear layer trips did not have any consistent effect on the ground-induced lift loss and again that temperature effects were negligible.

It is noted, however, that the difference between the small-scale and large-scale lift loss was reduced by about half with the new nozzle. Apparently there were changes in the setup that affected the flow to reduce the "scale effect." The available photographs of the test setup of reference 14 are photo copies with poor quality and are difficult to interpret. However, these photos suggest that there were obstructions near and on the "top" side of the planform. Although the velocity of the induced flow from "above" the model is very low, it is present, and perhaps not enough attention has been paid to obstructions in this region. An investigation of the effects of blockage above and around the model is needed.

The study of reference 14 also made a brief investigation of the effects of groundboard size. As shown in figure 21(d) increasing the size of the groundboard increased the suckdown measured with the 1/10 scale model. The suckdown for the small model with the increased groundboard are in fair agreement with the large-scale data, but this does not answer the scale-effect question because the large-scale setup did not use the larger groundboard.

CONCLUDING REMARKS AND RECOMMENDATIONS

This review of the data available on jet-induced suckdown in ground effect has not resolved the anomalies, but has hopefully brought them into better focus. Apparently, there are factors such as groundboard size, room size, jet characteristics, edge effects, etc., that are involved. Most of the reports on ground effect investigations do not define many of these conditions and operating parameters for their investigations.

A research program should be undertaken to study the suspected factors systematically. In order to provide a solid basis for analysis of the results these experimental studies should include, in addition to direct measurement of the jet thrust and suckdown, measurements of the pressure distribution on the ground as well as on the planforms, and flow visualizations and surveys of the wall jet profiles at various radial stations under the model and outboard of the model edge. The factors that should be investigated include:

1. Effect of surfaces above and near the model that may shield the "top" side of the model from the downflow induced by the wall jet.
2. Effect of groundboard size.
3. Effect of the shape of the edge of the model, including beveled, square, and rounded edges.
4. Effect of jet impingement angle.
5. Effect of nozzle-edge shape and of the gap between the model and the nozzle. This should be extended to large gaps to investigate the possibility of using gaps as a design tool to reduce suckdown.
6. Effect of the texture of the groundboard in the impingement region. This was not discussed above, but it has been suggested that a rough surface in the impingement region may reduce the energy and entrainment action of the wall jet.
7. Effect of the jet characteristics (turbulence, exit profile, and temperature, etc.) of the impinging jet on the formation, decay, and entrainment ability of the wall jet should be investigated and correlated with the suckdown.

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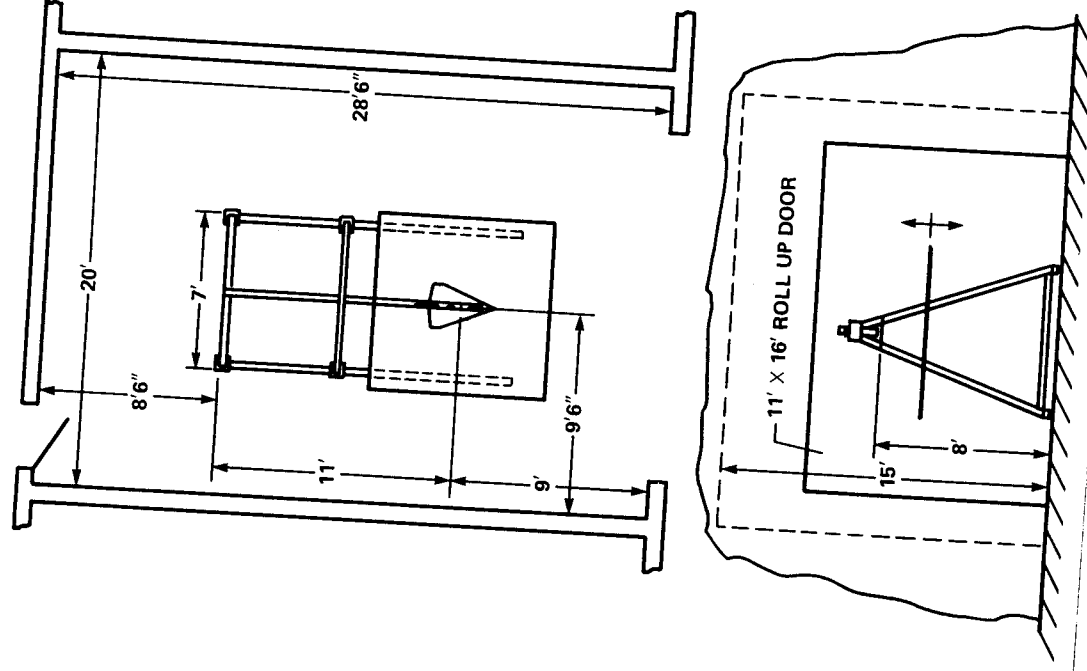


Figure 1. Test cell showing major dimensions and location of model support system and groundboard.

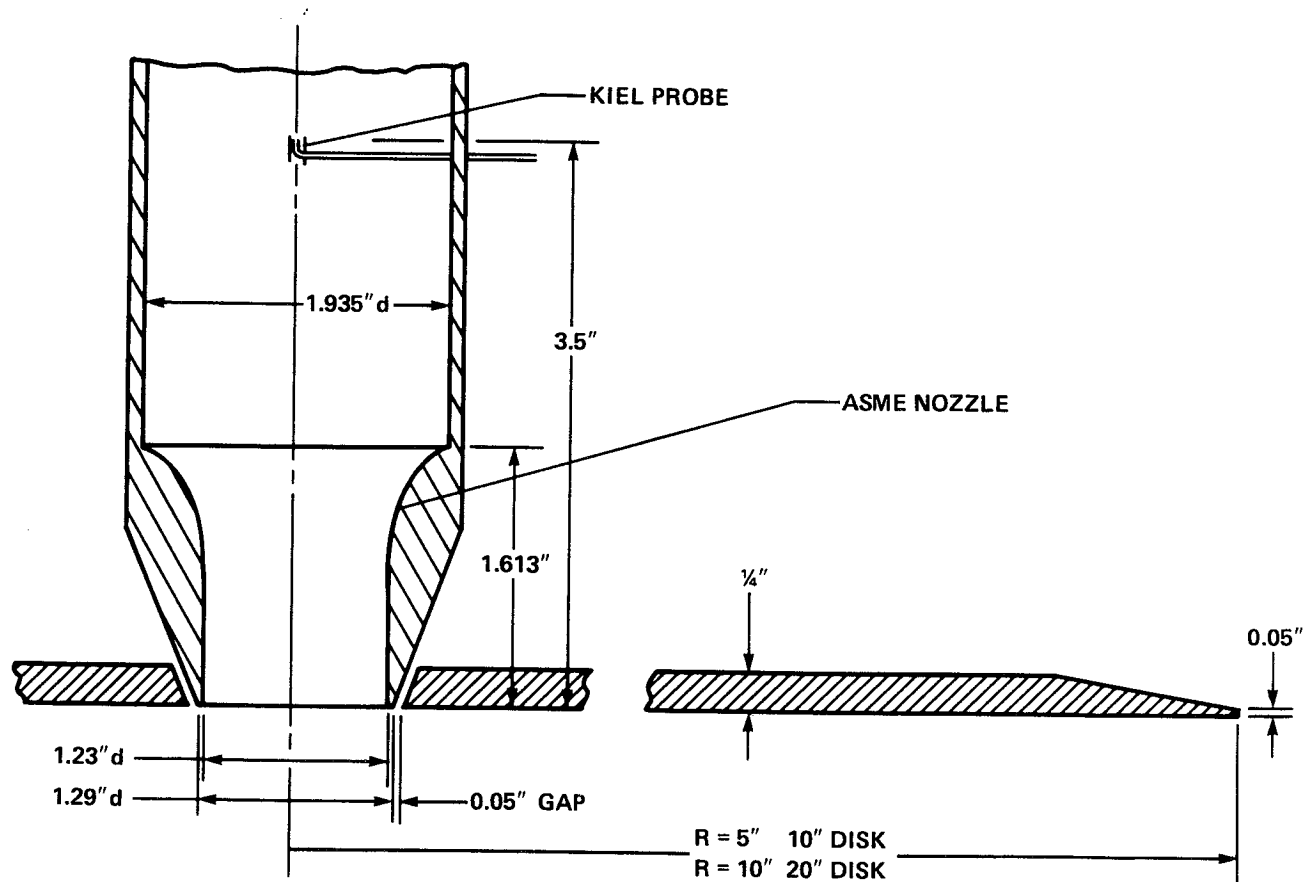
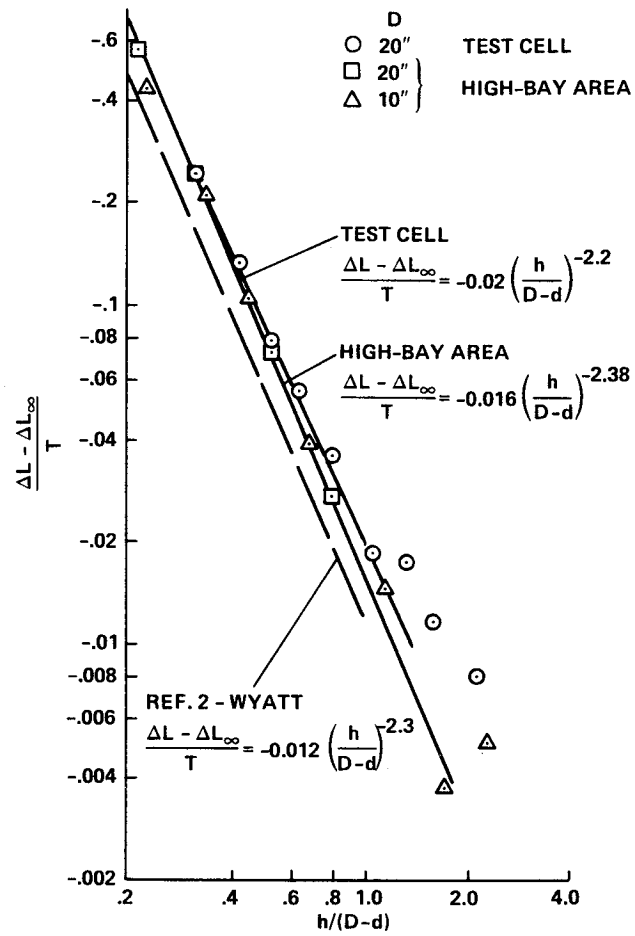
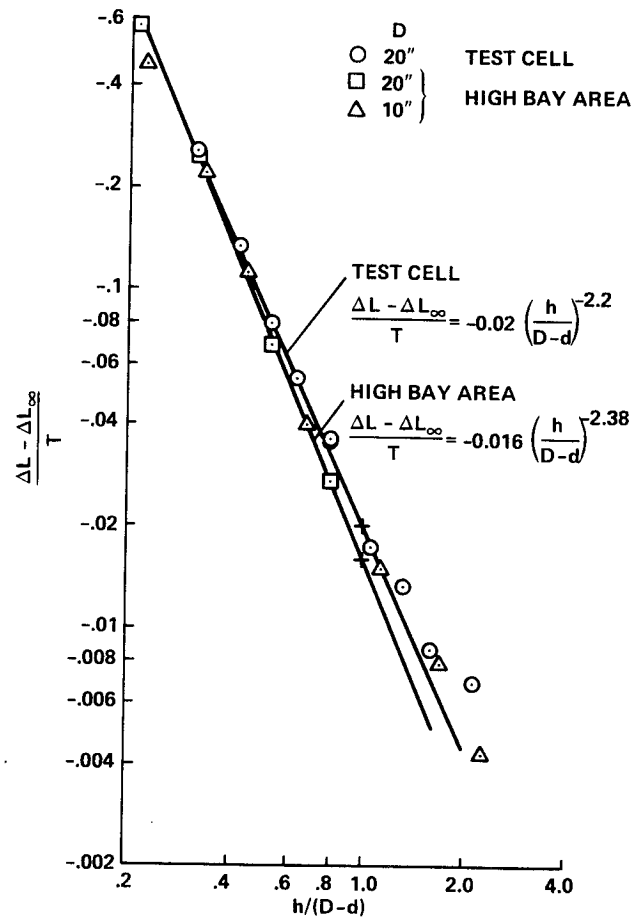


Figure 3. Principle dimensions of calibration plates and nozzle.



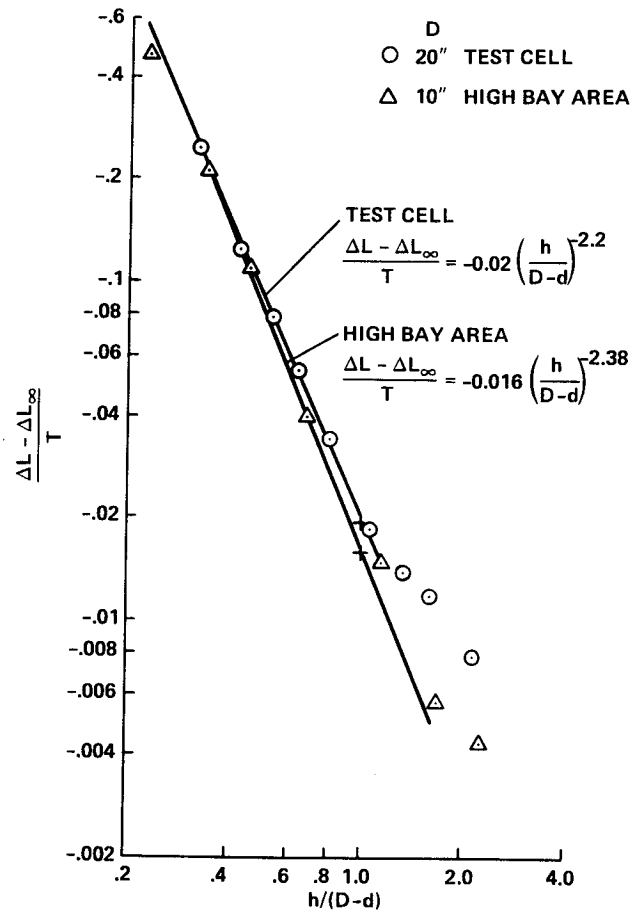
a) NPR = 1.5.

Figure 4. Effect of the size of the test facility on the lift loss induced by ground proximity.



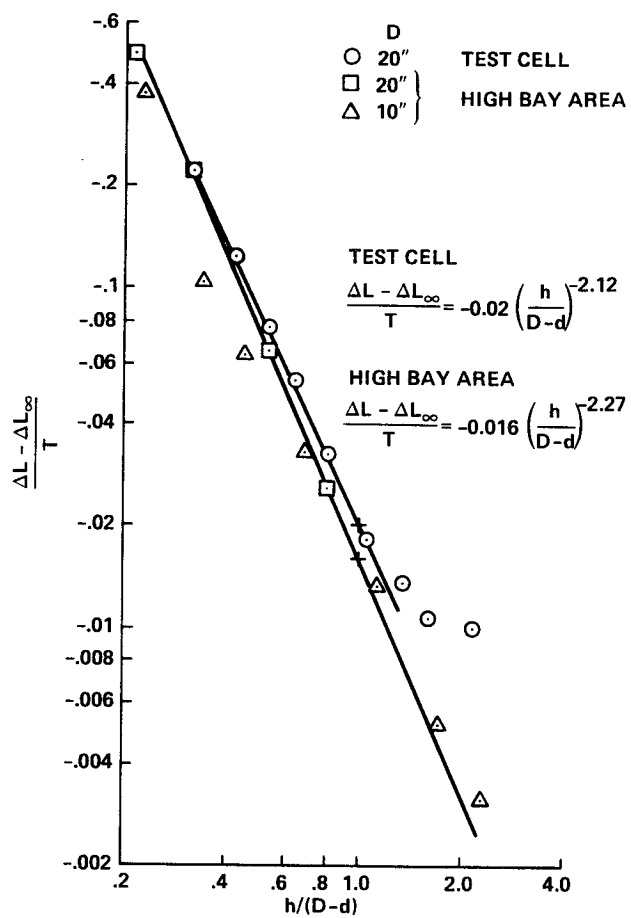
b) NPR = 2.0.

Figure 4. Continued.



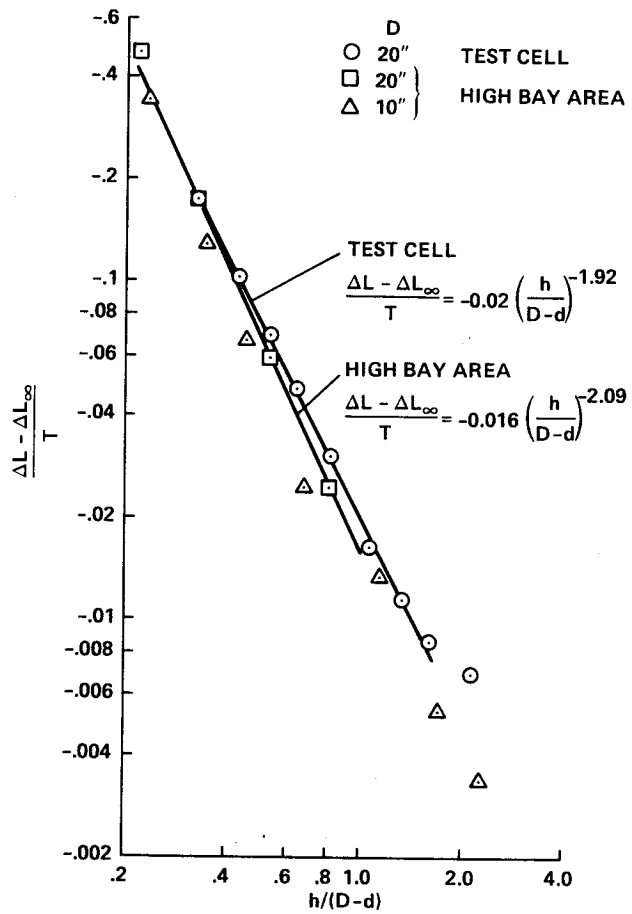
c) NPR = 3.0.

Figure 4. Continued.



d) NPR = 4.0.

Figure 4. Continued.



e) NPR = 6.0.

Figure 4. Concluded.

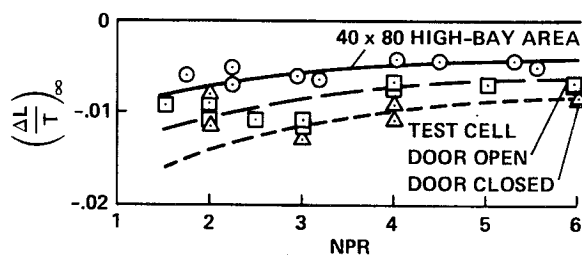


Figure 5. Effect of the size of the test facility on the lift losses induced out of ground effect.

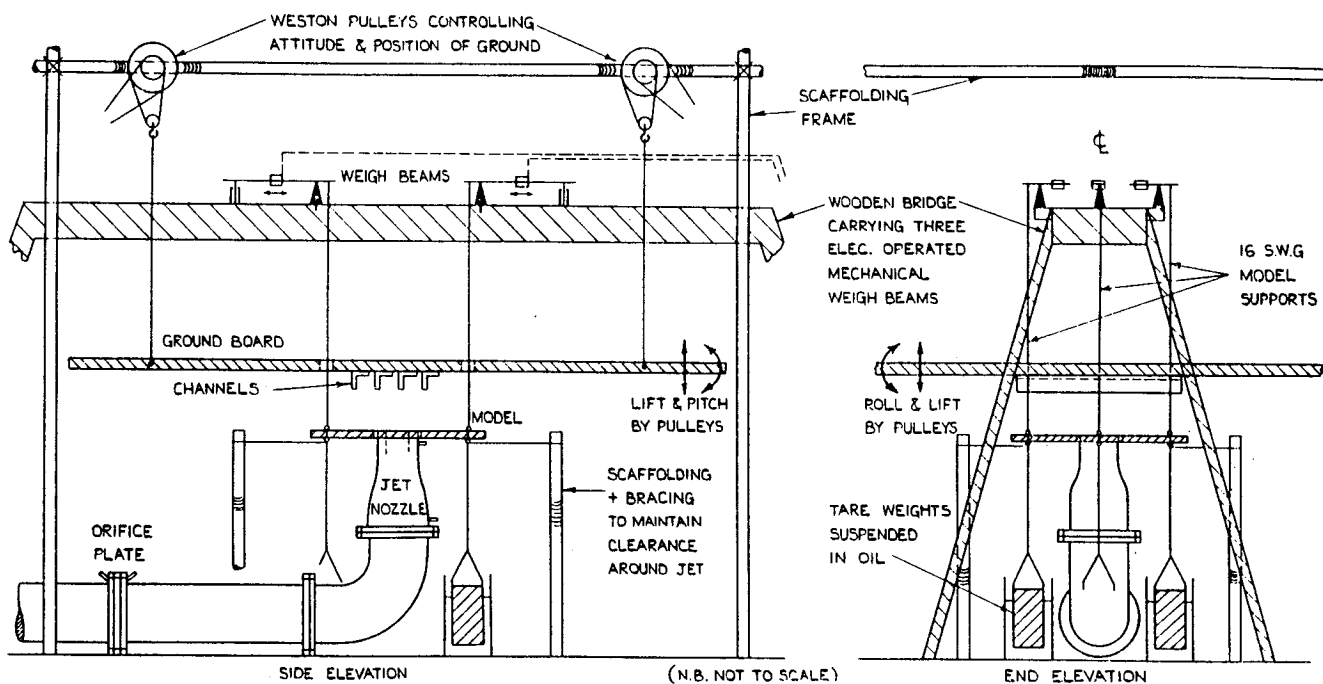


Figure 6. Sketch of the rig used in the reference 2 investigation. (reproduced from ref. 6)

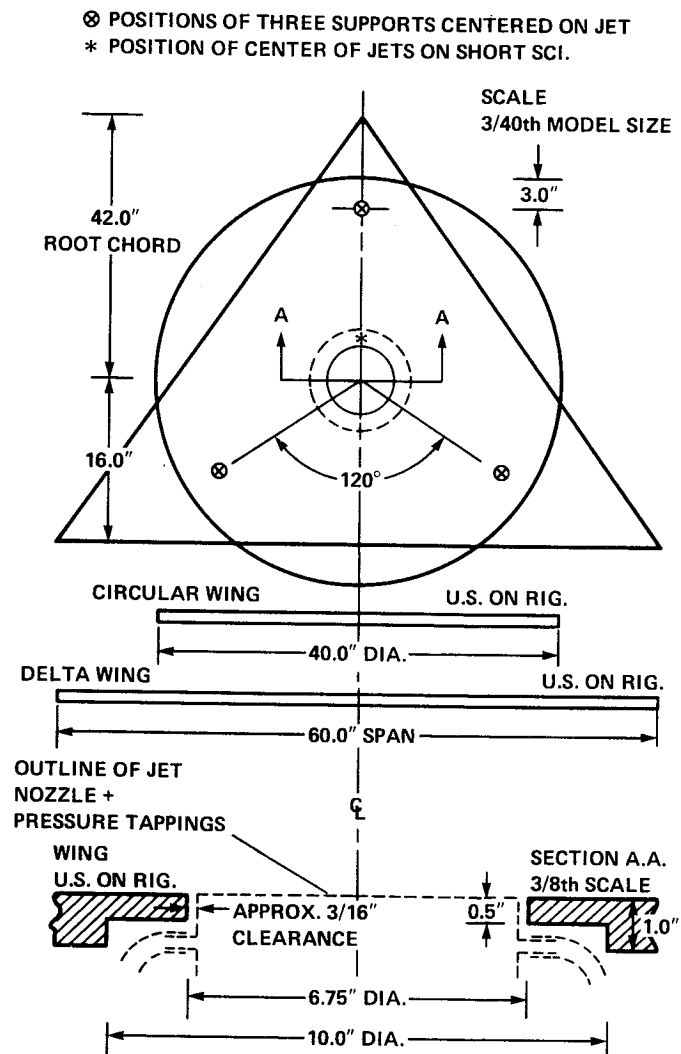


Figure 7. Details of models used in the reference 2 investigation. (reproduced from ref. 6)

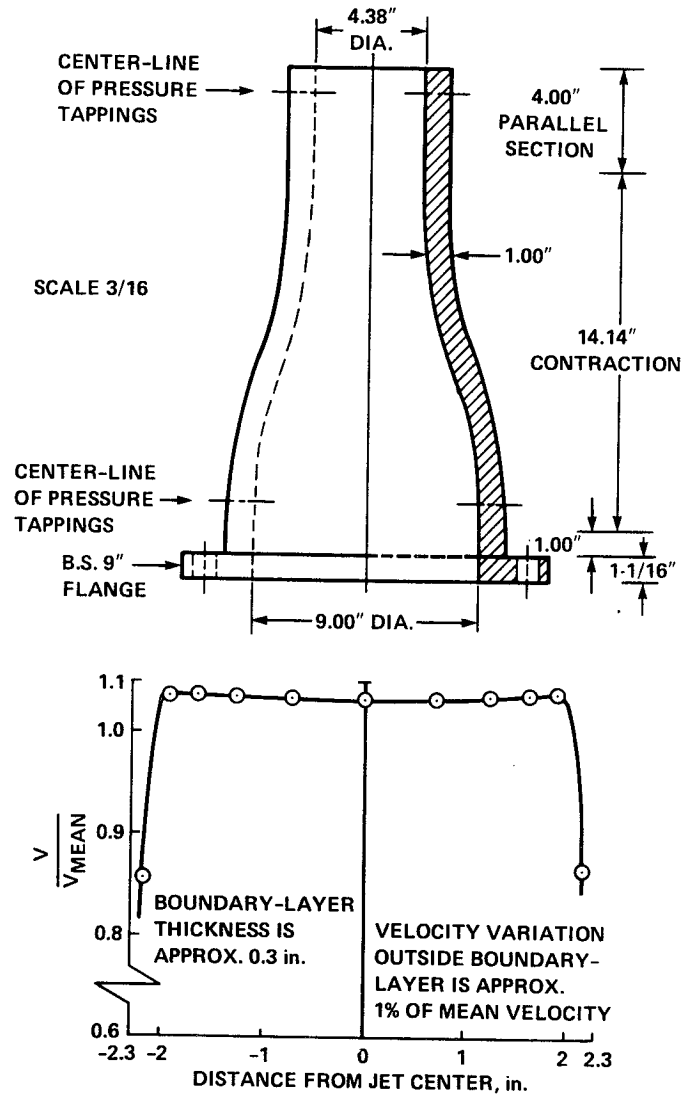


Figure 8. Section of nozzle used in reference 2 investigation with velocity profile at 0.31d from orifice. (reproduced from ref. 6)

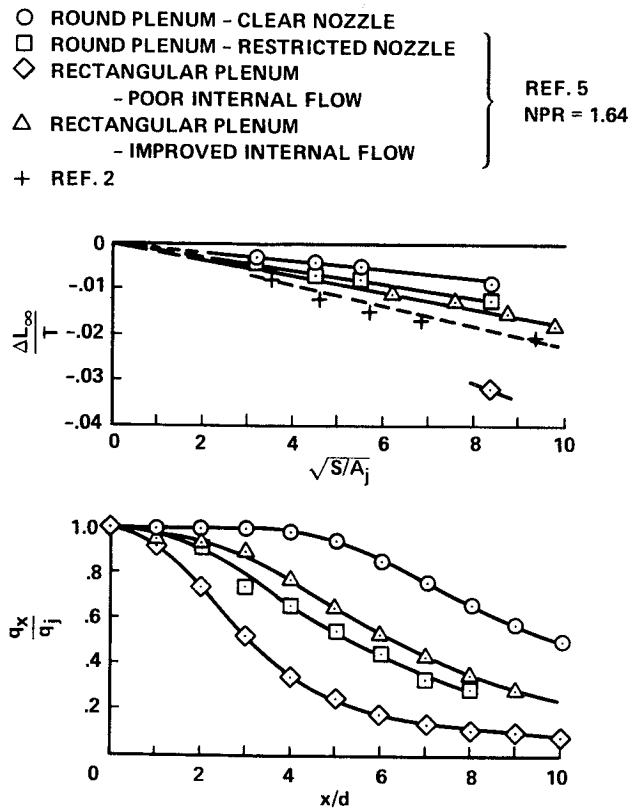


Figure 9. Effect of jet characteristics on decay rate and on the lift loss induced out of ground effect.

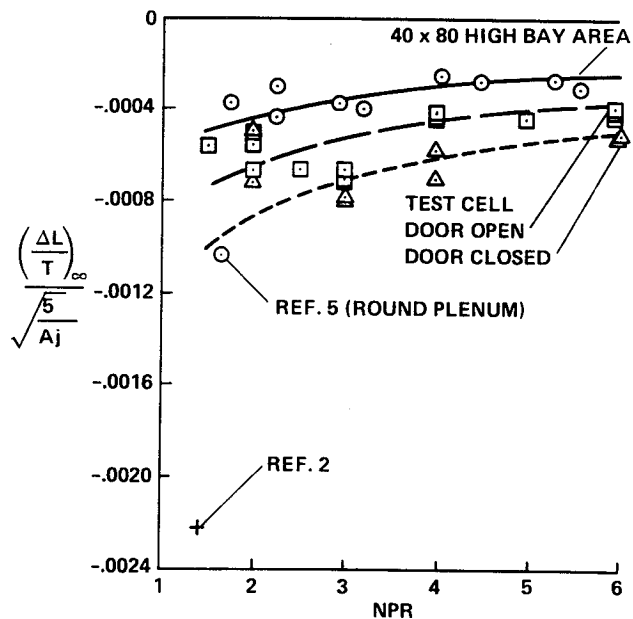


Figure 10. Comparison of lift loss induced out of ground effect in the present tests with that from references 2 and 5.

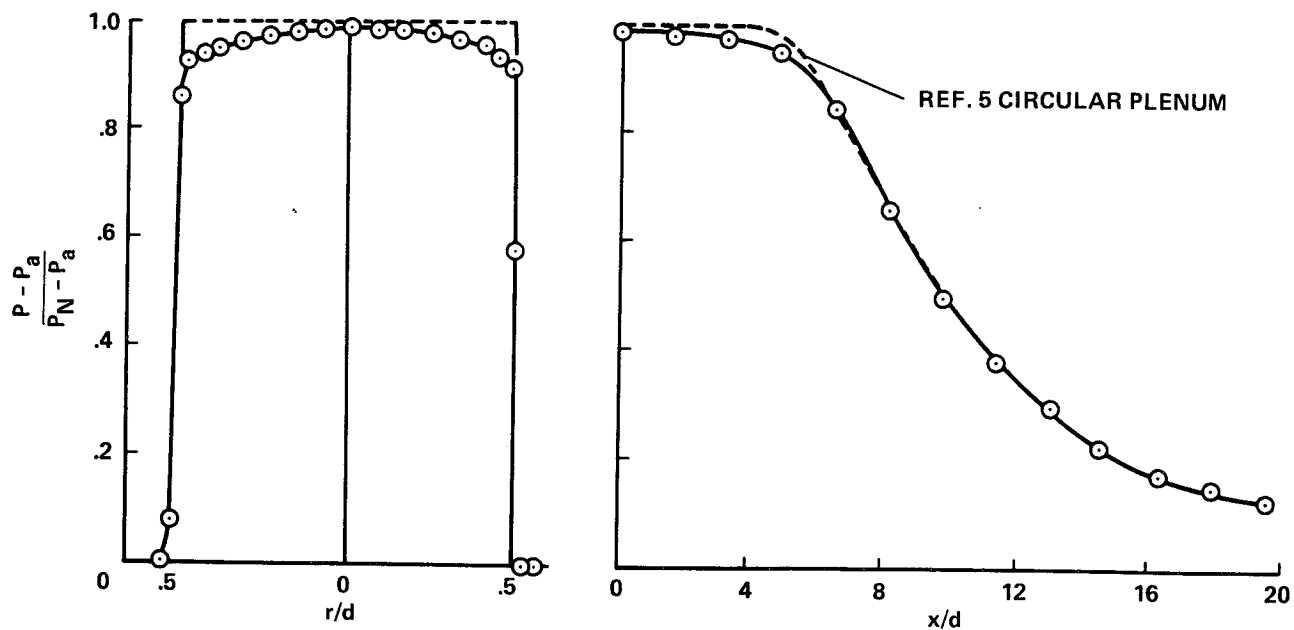


Figure 11. Exit dynamic pressure distribution and jet decay.

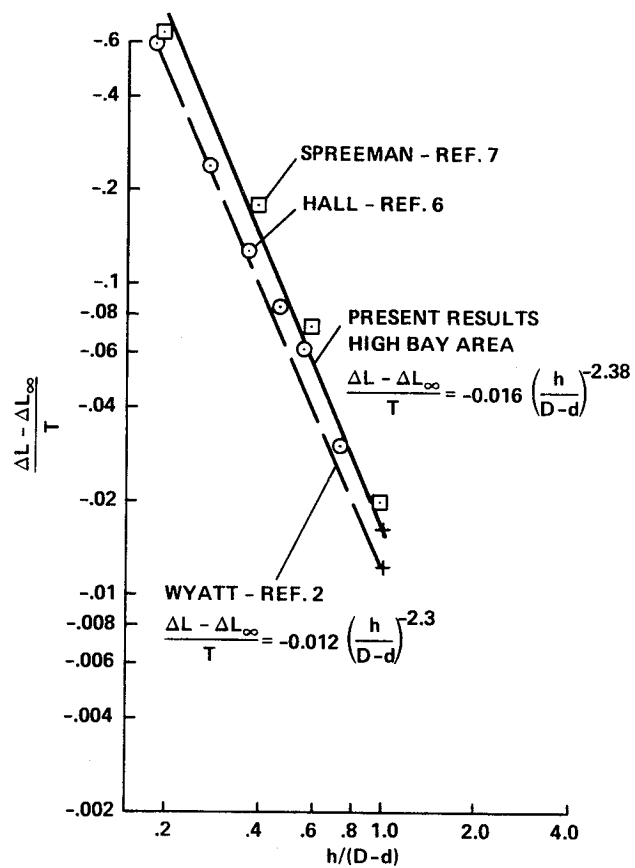


Figure 12. Comparison of large scale ground effect data from reference 7 with the data from the present tests and from references 2 and 8.

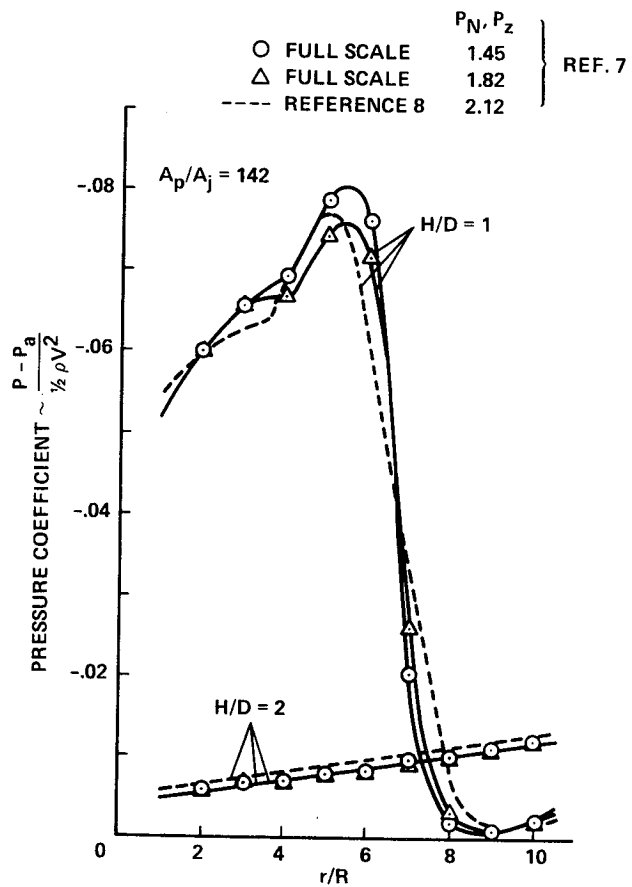
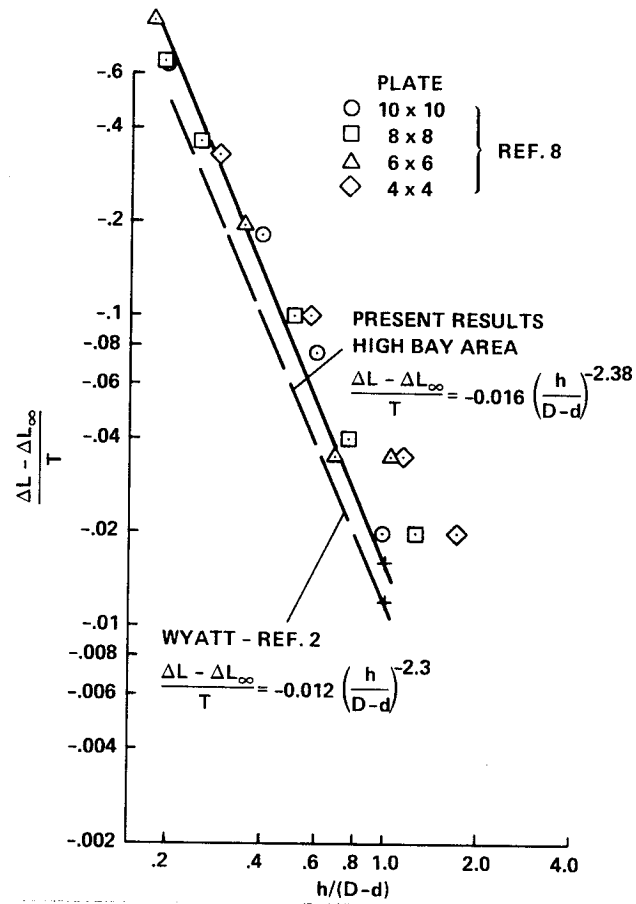
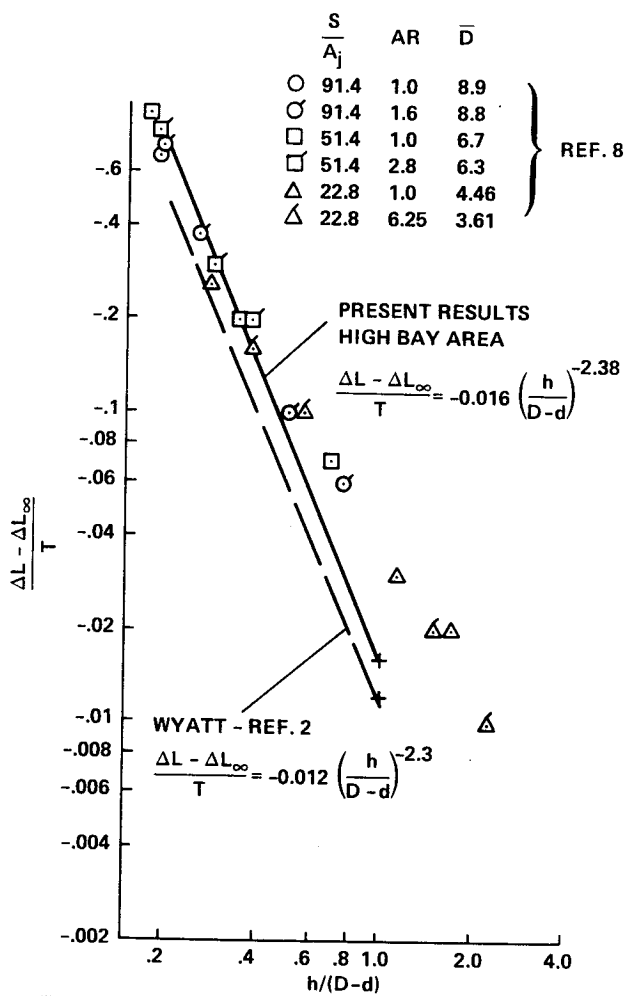


Figure 13. Comparison of the pressure distributions measured in references 7 and 8 (reproduced from ref. 7).



a) Square plates.

Figure 14. Comparison of the ground effect data from reference 8 with the data from the present tests and from reference 2.



b) Rectangular and square plates.

Figure 14. Concluded.

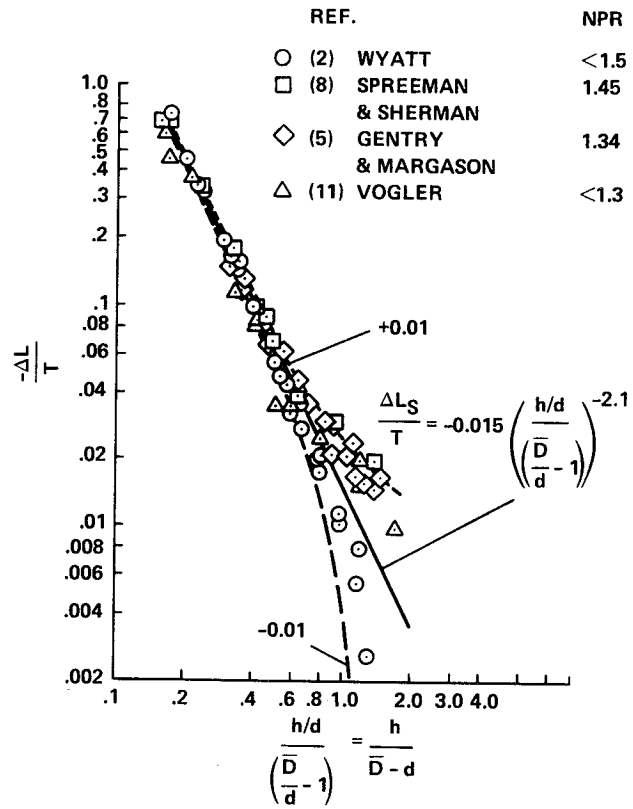
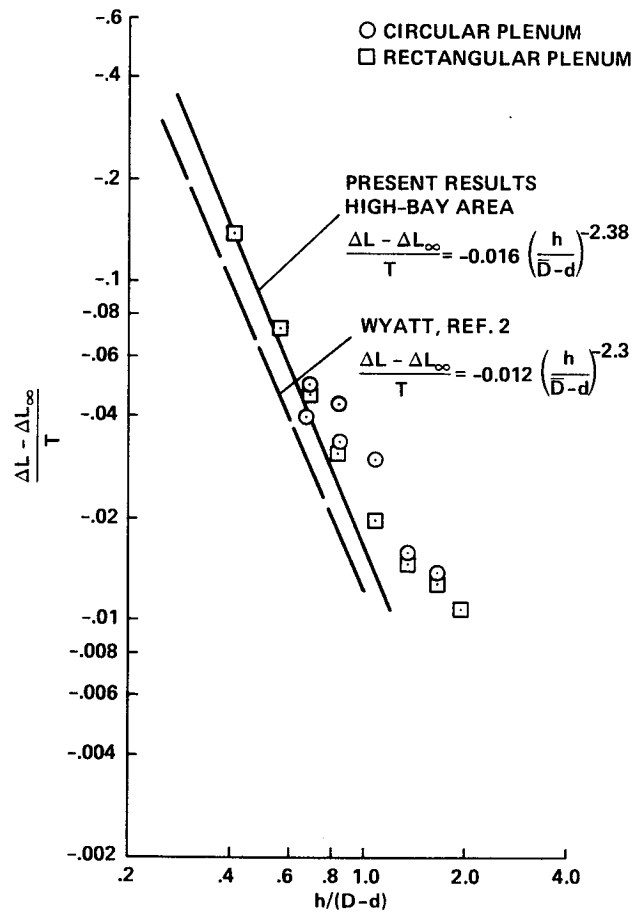
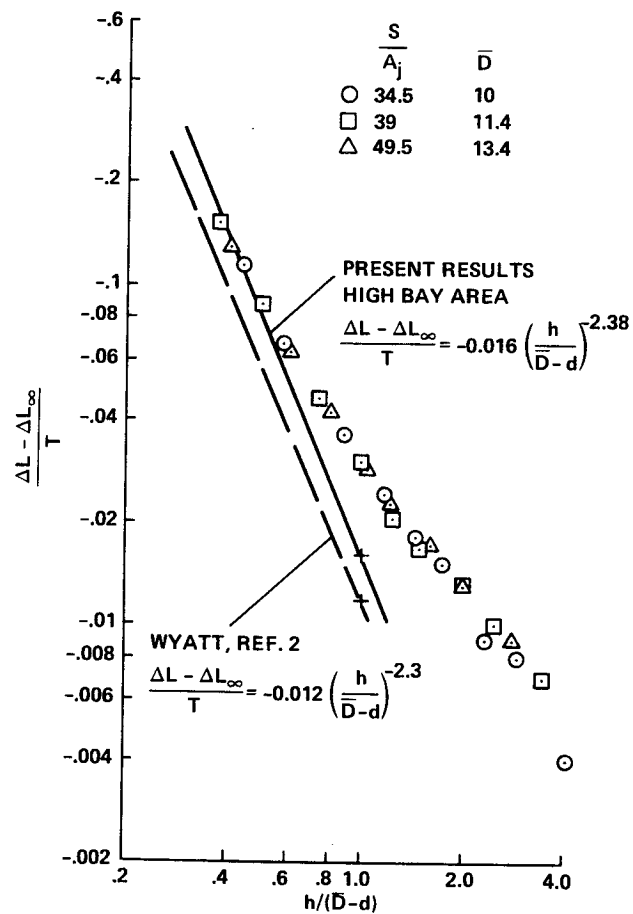


Figure 15. Data correlation presented in reference 10.



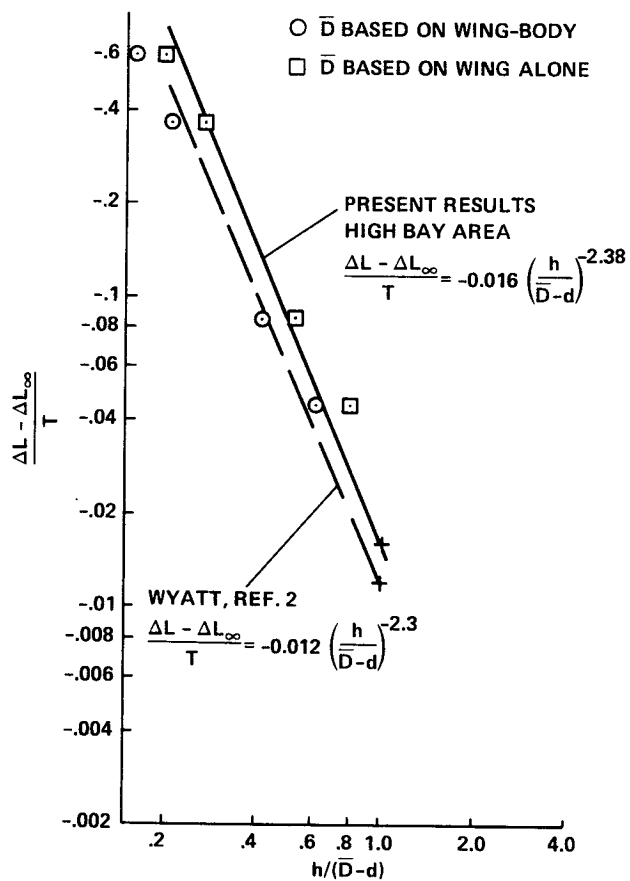
a) Circular planforms.

Figure 16. Comparison of the ground effect data from reference 5 with the data from the present tests and from reference 2.



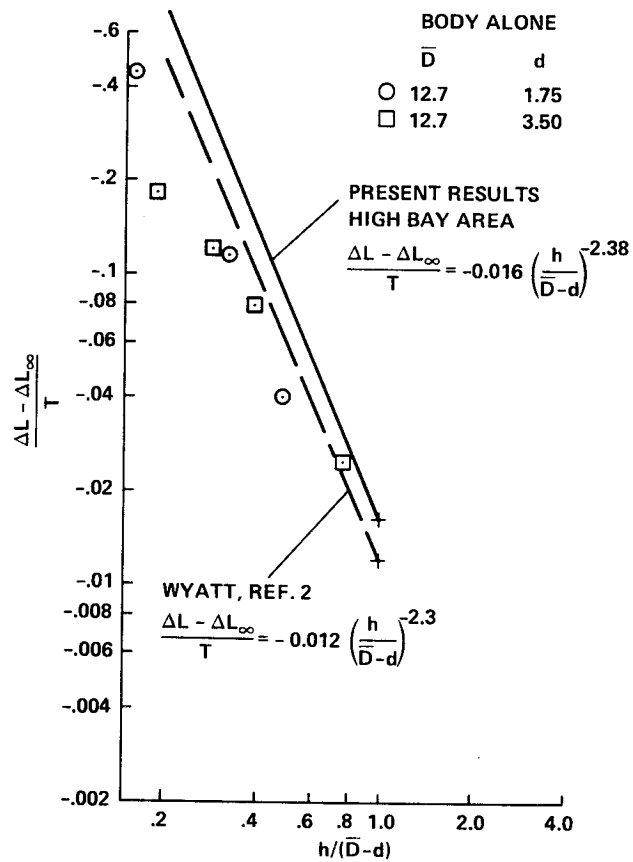
b) Wing-body configurations. (\bar{D} based on wing only)

Figure 16. Concluded.



a) Wing/Body configurations, reference 11.

Figure 17. Comparison of ground effect data from reference 11 with data from the present tests and from reference 2.



b) Body alone, reference 11. (\bar{D} based on body planform area)

Figure 17. Concluded.

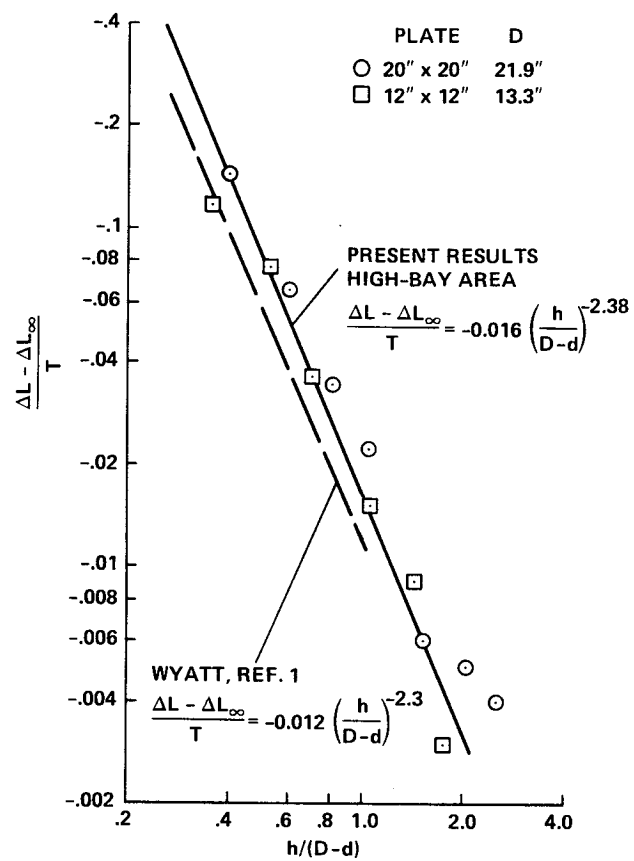


Figure 18. Comparison of ground effect data from reference 12 with data from the present tests and from reference 2.

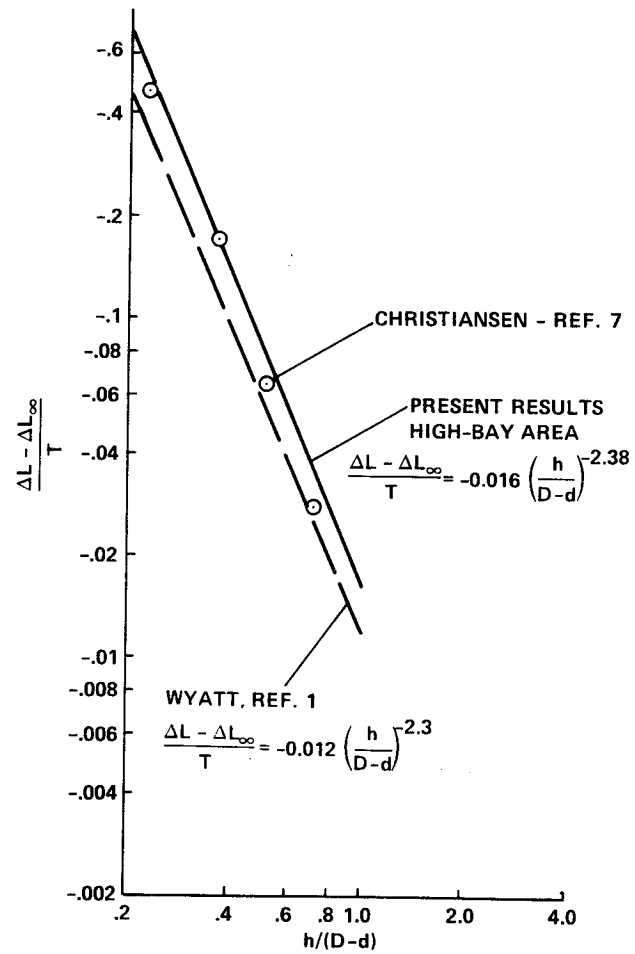


Figure 19. Comparison of large scale data from reference 13 with data from the present tests and from reference 2.

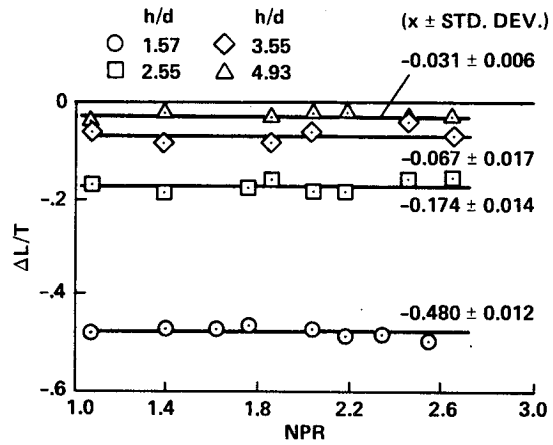
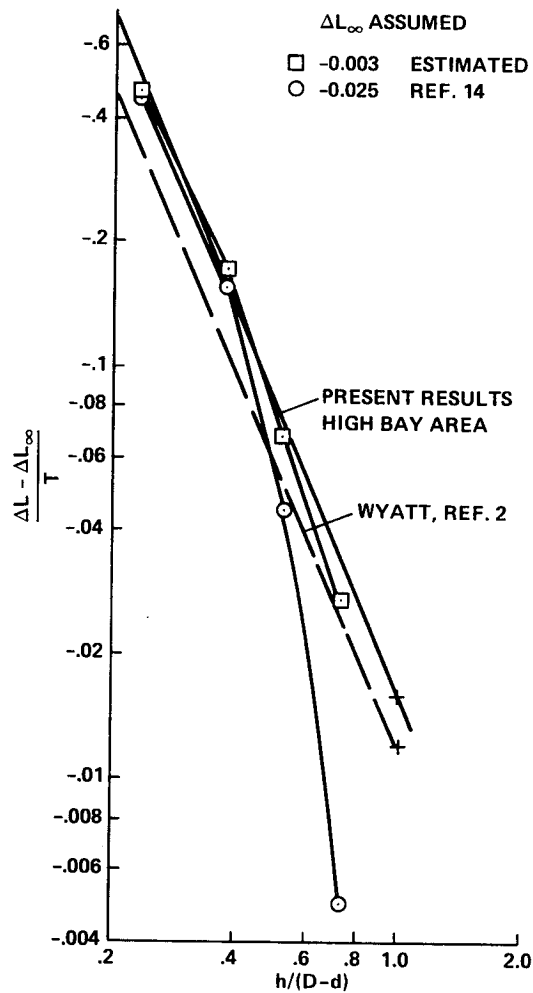
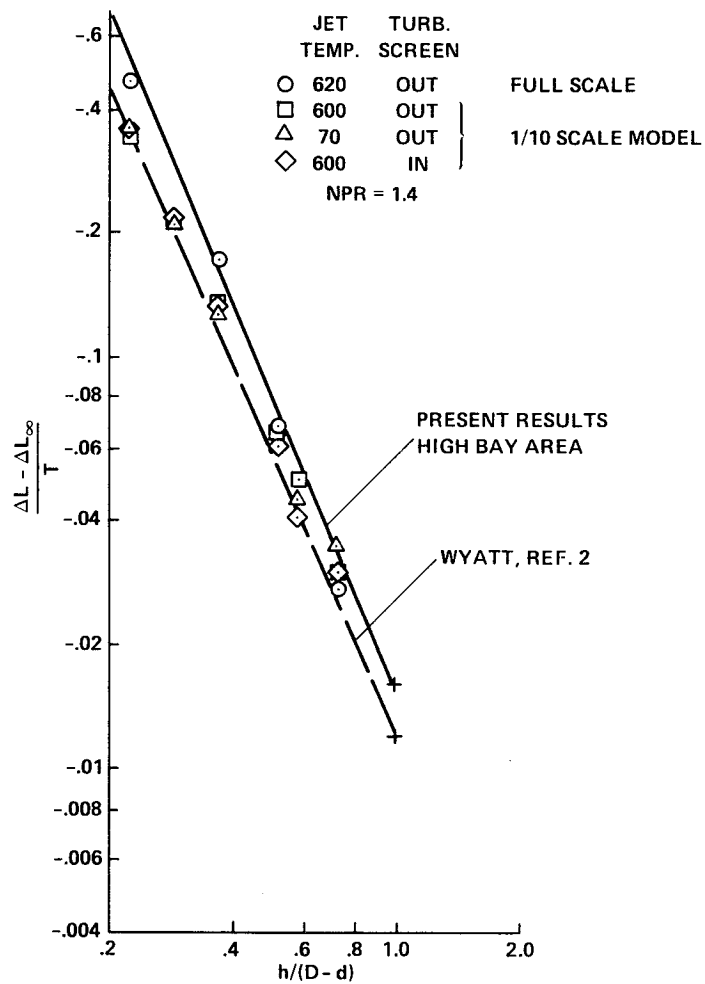


Figure 20. Effect of pressure ratio on lift loss in ground effect, reference 13.



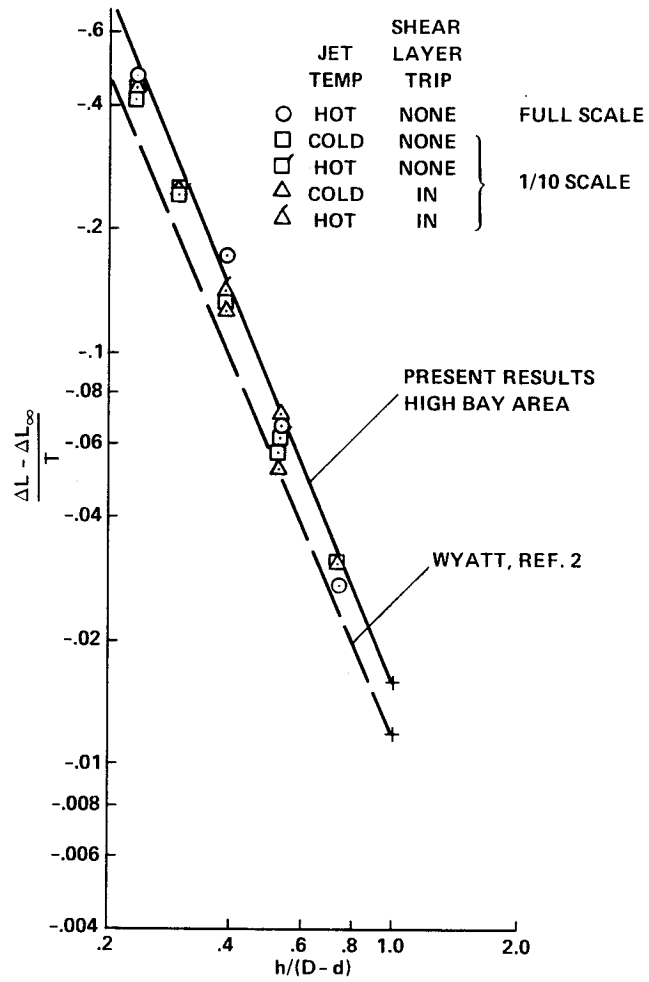
a) Large scale data (J-97 engine); Sensitivity to out-of-ground-effect lift loss.

Figure 21. Results of scale effects study by Benepe.



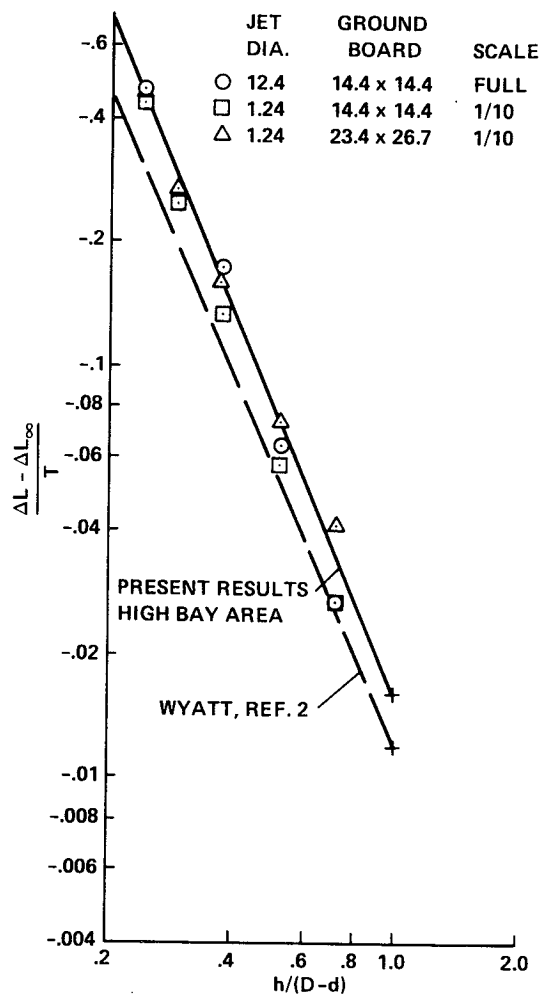
b) Initial model results.

Figure 21. Continued.



c) Second model results.

Figure 21. Continued.



d) Effect of groundboard size.

Figure 21. Concluded.

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13. ABSTRACT (Maximum 200 words) The data from nine different investigations of the suckdown induced in ground effect by a single jet issuing from plates of various sizes and shapes have been examined and compared. The results show that the generally accepted method for estimating suckdown significantly underestimated the suckdown for most of the configurations. The study identified several factors that could contribute to the differences. These include ground board size, plate edge effects, jet flow quality, jet impingement angle, the size of the chamber in which the tests were run, and obstructions in the region above the model. Most of these factors have not been investigated and in many cases items such as the size of the test chamber, jet flow quality, ground board size, etc., have not even been shown in the documents reporting the investigation. A program to investigate the effects of these factors is recommended.				
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